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Determine, for a broad range of frequencies (nominally 10-100 kHz), the limitations imposed by the oceanic environment on the exploitation of coherent signal structure. This understanding is required in order to optimize sonar signal processing structures (e.g. channel conditioning, especially in shallow water), for wideband signal and processor design, and for acoustic propagation modeling.

Develop the capability to preduct the dynamic and spatial characteristics of wakes and the acoustic field behavior in and around the wakes of Navy warships. Seek a predictive capability for how acoustic propagation varies with frequency, source-receiver geometry relative to the wake, and the spatial statistics of attenuation and scattering strength in the wake.

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High Frequency Acoustics and Signal Processing for Weapons

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LONG-TERM GOALS

Task 1: The long-term goal of this task is to determine, for a broad range of frequencies (nominally 10-100 kHz), the limitations imposed by the oceanic environment on the exploitation of coherent signal structure. This understanding is required in order to optimize sonar signal processing structures (e.g. channel conditioning, especially in shallow water), for wideband signal and processor design, and for acoustic propagation modeling.

Task 2: The long-term goal of this project is to develop the capability to predict the dynamic and spatial characteristics of wakes and the acoustic field behavior in and around the wakes of Navy warships. We seek a predictive capability for how acoustic propagation varies with frequency, source-receiver geometry relative to the wake, and the spatial statistics of attenuation and scattering strength in the wake.

OBJECTIVES

Task 1: Since coherent signal processing relies on the signal remaining coherent while the interference is incoherent, the experimental and theoretical objectives focus on signal coherence as a function of (elapsed) time and frequency (separation and/or bandwidth), and in particular, effect of the medium and development of a predictive capability. The scientific objectives of this task are to:
1. Directly measure the acoustic time and frequency coherence of individual paths in an ocean channel while varying the signal bandwidth and center frequency, as well as the source-receiver geometry, concurrently characterizing the ocean boundaries and volume
2. Investigate the physical mechanisms which impact propagation through the ocean channel and which limit acoustic coherence
3. Develop acoustic propagation models which can be used to correctly predict acoustic coherence
4. In the far term, investigate signal processing architectures which exploit knowledge of oceanic time and frequency behavior

Task 2: The scientific objectives are to understand and develop satisfactory models for (1) the spatial and temporal variation and bubble size distribution found in warship wakes and (2) acoustic propagation through the complex in-water media comprising a warship wake.

APPROACH

Task 1: Our approach to measuring temporal coherence utilizes a single pure tone (PT) or FM sweep signals transmitted every 128ms for several seconds. PT pulse lengths are 0.1ms to 2.0ms; FM

bandwidths are 500Hz to 13kHz and pulse lengths are 8ms. Center frequencies are 18kHz to 70kHz. Signal are transmitted from, and received at, stable platforms so that only ocean effects cause variation over the transmission interval. The received signal consists of groups of arrivals (e.g. direct path, surface bounce, etc.), with each group separated by 128ms. The correlation between different groups of arrivals or simply between components (e.g. surface bounce arrivals) in different groups provides a direct estimate of temporal coherence, either of the group or of subset of the group. In either case, our procedure is to normalize correlation by the energy in the two windows in order to obtain coherence values between 0 and 1. The pulse widths cited above were dictated by the available water depth at the test site used for the 2000 experiment, and may be revised for future tests.

This approach is valid for one-way and two-way (or bistatic) propagation, although any decorrelation or spread introduced by the scatterer would affect results for the latter case. In the past we have shown results of coherence measurements made at a shallow site in the North Sea and a deeper site in the Mediterranean Sea. In general, we have found temporal correlation to remain high (>50%) for larger bandwidths and longer times than intuition had led us to expect. There are a few published measurements of temporal or frequency coherence [1-5]. An interesting aspect of our work is that we utilize 10's of kHz signal frequencies and bandwidths up to 13kHz, a significantly greater bandwidth than that used by earlier researchers.

Task 2: The US Navy's development of an anti-torpedo torpedo (ATT) relies upon simulation as well as in-water tests to predict ATT performance against threat torpedoes. Simulating engagements against wake homing torpedo threats requires the capability to predict acoustic propagation through the wakes of surface ships. The acoustic characteristics of the ship wake can be obtained from either a Coastal Systems Station (CSS), Panama City hydrodynamic and bubble transport model or from uplook sonar measurements across the wake; both the wake model predictions and measurements require interpolation between cross-wake cuts spaced 100 or more meters apart. However, range-independent ray tracing has been unable to produce acoustic propagation predictions that match in-water measurements.

Our approach has been to improve both the wake hydrodynamic and bubble field description and the acoustic propagation model, and to develop a fast, in-house capability to evaluate effects of the wake bubble field on acoustic propagation. Considering first improvements to the wake hydrodynamic and bubble field description, we have developed a full-two-fluid bubbly flow model based on modern multiphase Computational Fluid Dynamics (CFD) technology with application to surface ship propulsors. With a view towards our ultimate goal of in-house capability, we were encouraged by Dr. Edwin Rood, who directed the ONR Free Surface Turbulence and Bubbly Wakes program (currently run by Dr. L. Patrick Purtell), to focus on the propulsor, as this was an outstanding technology need area for the program. In FY '02, we plan to contribute the ARL propulsor tool to overall ship wake hydro analysis, by integrating with other 6.1 (Rood/Purtell) program tools. In particular, we are proposing to Dr. Purtell that we directly integrate the CFDSHIP-M code, originally written by ARL researcher Dr. Eric Paterson, with the ARL propulsor technology developed under this program. We anticipate Dr. Purtell's support, because this integration will support the CSS model and current research in ship wake hydrodynamics.

Improvements to modeling acoustic propagation through the wake have focused on a parabolic approximation to the wave equation (PE) because of its capability to deal with range and depth-dependent media. In prior years, an existing two-dimensional PE model [1] was adapted for use in the ship wake [2] and applied to a simple, unclassified 3D random wake acoustic field developed from open literature sources [3]. The 2D PE predictions provided much better agreement with in-water data, but it was apparent that a 3D propagation model would be required to properly predict thee acoustic field produced by a 3D ship wake, and development of a 3D PE model was initiated in FY01.

WORK COMPLETED

Task 1: In October-November 2000, in collaboration with the Marine Physical Laboratory of Scripps Institution of Oceanography (MPL/SIO), a temporal and spectral coherence measurement (BBCoh) was conducted in the Pacific Ocean roughly 35 nm west of San Diego (32°38.3′N, 117°57.9′W). Special effort was made to minimize projector and hydrophone motion. MPL/SIO's Floating Instrumentation Platform (FLIP) (http://www-mpl.ucsd.edu/) in a 3-point moor provided a stationary projector mount, while a bottom-moored buoy with an elastic mooring provided a stable mount for a four-element hydrophone string (Figure 1). A high bandwidth radio frequency (RF) link was used to transmit data from the hydrophones to FLIP.
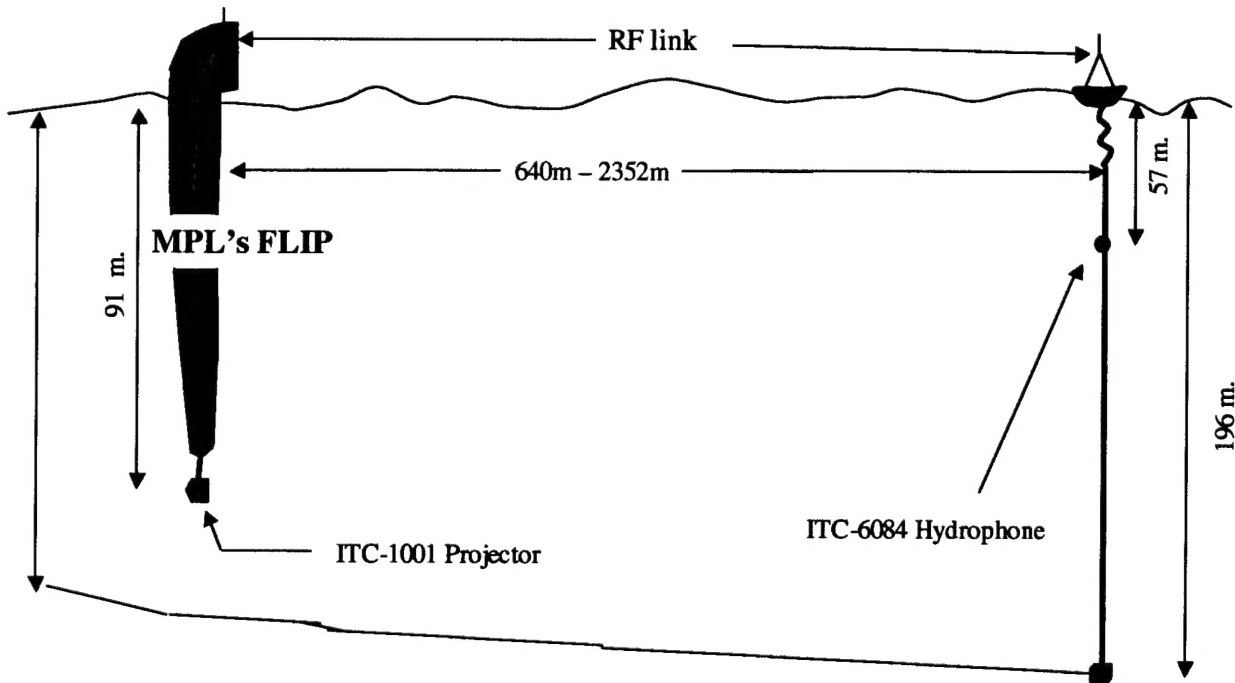

Figure 1: Oct-Nov 2000 BBCoh geometry. The transmitter was located on MPL/SIO's FLIP, which was in a three-point moor. Receive hydrophones were mounted on the riser of an elastically moored surface buoy. Received signals are sent via RF link to FLIP.

The water depth was 196m at FLIP's location; the projector depth was 91m. The receive hydrophone array was deployed twice, once 640m away from FLIP in 172m of water, and a second time at 2352m from FLIP where the water depth was 742m. An extensive environmental data collection effort included directional surface waveheight, continuous ocean temperature measurements at 4m intervals from 5m to 65m depth, and acoustic Doppler current profiler (ADCP) measurements of ocean current. A 15-element towed CTD chain had not been received in time for this experiment, but will be used in future experiments.

Task 2: Wake hydrodynamic and bubble field modeling. In FY '01 a first of its kind computational capability was developed and demonstrated for bubbly propulsor flow CFD analysis. In particular, as demonstrated below, we have extended and applied the in-house multi-phase CFD code, NPHASE, to perform fully unstructured, full-two-fluid, multiple bubble size, full unsteady rotor-stator, full annulus/stage, three-dimensional, parallel, second order accurate in space and time analyses of a realistic multiple blade ducted propulsor configuration. This work involved two graduate students (Dan

Cameron, M.S. in Mechanical Engineering 12/01, Wen-Sheng Yu, Ph.D. in Aerospace Engineering, 12/01) and resulted in three open literature publications listed below.

Wake acoustic propagation modeling. Beginning with a 3D PE code developed for atmospheric propagation [5], a theoretical approach to 3D propagation through the ship wake using PE was developed. The existing code required modification to accommodate (1) a pressure release boundary condition at the ocean surface rather than a finite impedance condition at the air-ground interface; (2) the 3D distribution of turbulence in the ship wake rather than the homogeneous, isotropic distribution of turbulence used for the atmosphere; and (3) projector directionality in elevation and azimuth, since directionality in elevation only is utilized in the atmosphere. Testing of the 3D code began in FY01 and will continue in FY02.

RESULTS

Task 1: Data recorded with the buoy 640m from FLIP contained direct and surface bounce paths that could be resolved prior to correlation processing. An example is shown in Figure 2 [6]. The top panel shows the envelope of groups of arrivals spaced 128ms apart. The bottom panel is an expanded view showing two groups, each containing an identifiable direct path (DP) and surface reflected (SR) arrival. The DP arrival is approximately 8ms long and shows minimal interference effects. The SR arrival, on the other hand, is extended and irregular due to interaction with the surface. This data clearly shows that for this test site, 8 msec was the longest pulse that could be used without causing overlap between the direct and surface paths. If overlap were allowed, proper normalization of the resulting replica correlation peaks(one measure of coherence) would not have been possible.
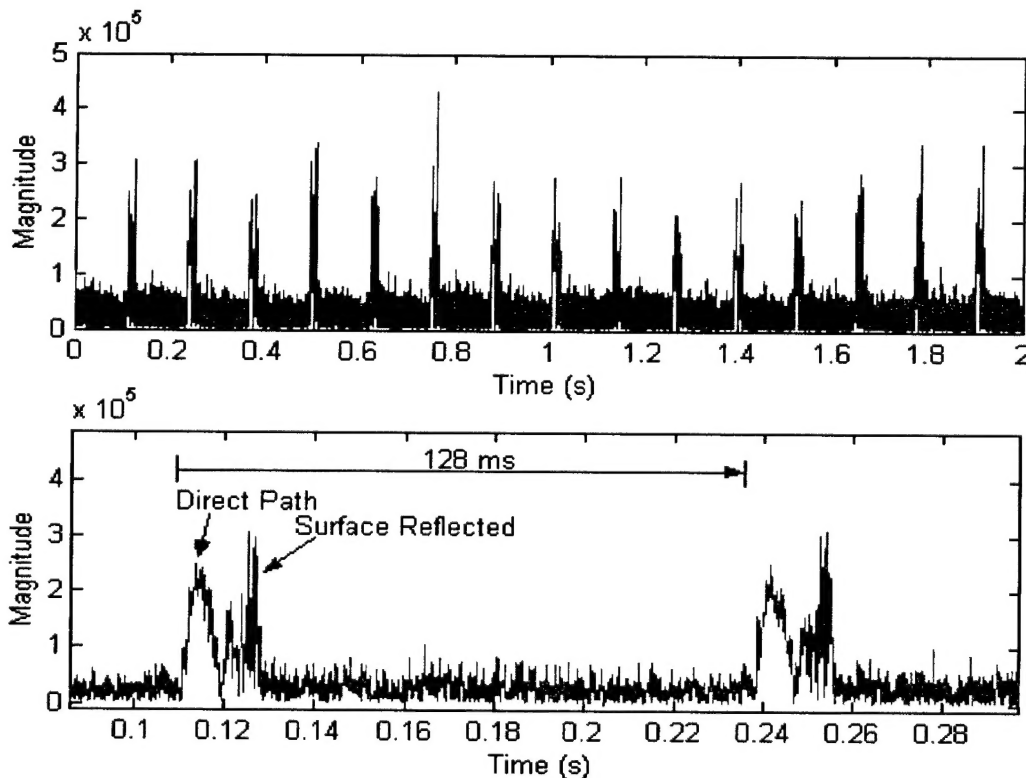

Figure 2: FM signals (8ms, 7kHz bandwidth, 18kHz center frequency) received 640m from the projector. The bottom bounce path not visible in the raw time series. Signal rep rate is 128ms. Top: 2s of received data. Bottom: Expanded view of .29s segment containing 2 transmissions.

A 40-hour segment containing FM signals with 18kHz, 32kHz and 46kHz center frequencies and 5kHz to 13kHz bandwidth was correlated with the transmitted signal. Wind speed showed variation during the 40-hour period, ranging from 4 to 12 knots, and significant wave height remained near 0.8m. Figure 3 shows correlation of the 18kHz signals averaged over 2s to 4s intervals. The top panel shows results for the direct path, while the lower panel shows results for the surface reflected signal. None of the curves display a particular dependence upon time. However, correlation decreases with increasing bandwidth for both the DP and SR arrivals, and much more so for the SR signals. Similar results were obtained using 32kHz and 46kHz signals.
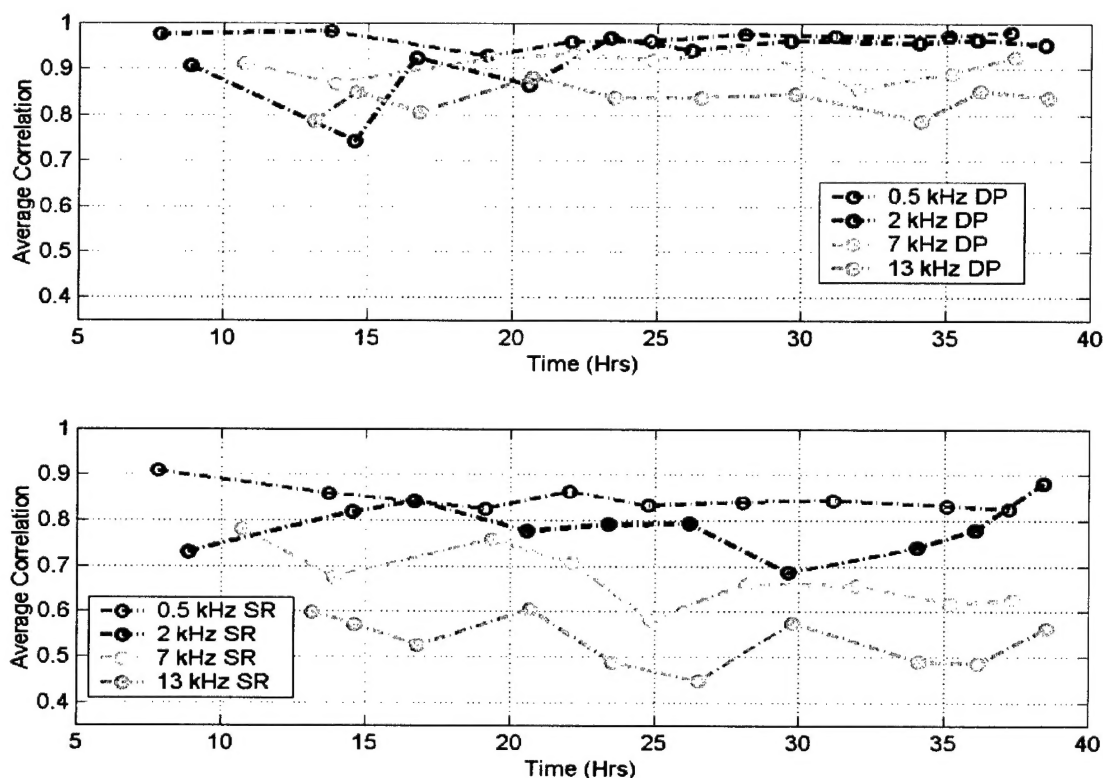

Figure 2: Correlation averaged over 2s to 4s periods for 18kHz FM signals. Source-receiver range is 640m. Top panel shows results for the direct path (DP) arrivals. Bottom panel shows results for the surface reflected (SR) arrivals. SR correlation shows strong bandwidth dependence.

Figure 3 shows the relationship between correlation and signal bandwidth for 18kHz, 32kHz and 46kHz signals that have been forward scattered by the ocean surface. Clearly correlation goes down as bandwidth is increased. Figure 3 also shows the prediction from available theory, which was developed almost 30 years ago based upon measurements with bandwidths up to 2kHz [1]. The theory does not agree particularly well with the measurements for higher bandwidths, possibly because of shadowing which is not considered in the work reported here *theory* but may be affecting our results. A revision to the theory is one focus for FY02.

Task 2: Wake hydrodynamic and bubble field modeling. Technology development for FY '01 include the implementation of suite of interfacial bubble force models, including interface exchange due to drag, several non-drag forces, mass transfer, and turbulence. Significant numerical issues were addressed and tackled including source term (i.e. force and mass transfer) treatment, new findings

related to numerical discretization of "collective" forces (such as lift), artificial dissipation issues, and inter-field coupling. This work was the principal topic area of two the three papers published.

Figures 1 and 2 provide sample results of the capability established in FY '01 for propulsor bubbly flow CFD modeling. Since bubbly propulsor flow data does not exist, code validation studies were carried out separately for single-phase propulsor analyses and bubbly-flow in non-turbomachinery. Figure 1a shows predicted pressure distribution vs. experiment for the midspan section of the HIREP axial pump stator. Figure 1b shows predicted bubble volume fraction profiles vs. experiment for a bubble column reactor. In concert, these results, and numerous others obtained in FY '00 and '01, serve to provide some validation of the code for bubbly propulsor flows. Figure 2 shows elements of an unstructured, multi-phase, 6-field (bubble sizes of 20, 50, 100, 200, 500 μm solved for), unsteady rotor-stator interaction simulation of the complete HIREP stage. As mentioned above, we feel that this demonstrates a first-of-its kind computational capability.
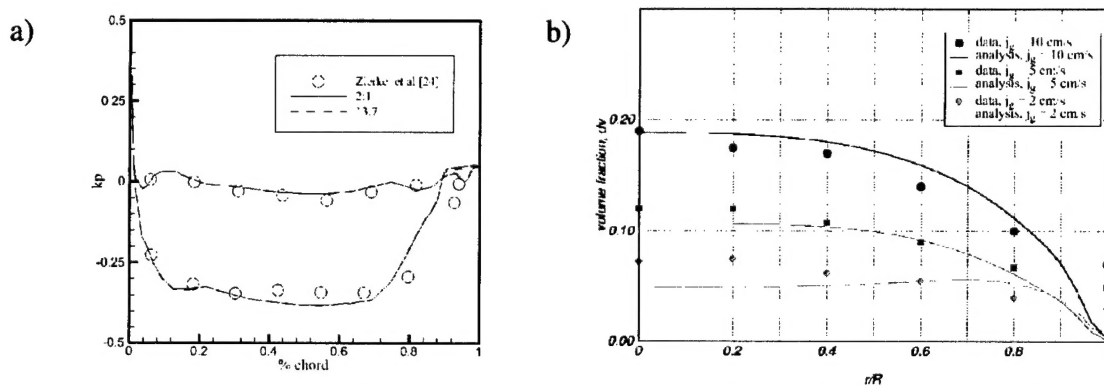

Figure 1. Elements of bubbly-propulsor-flow-relevant NPHASE validation studies. a) Predicted (single-phase analysis) vs. measured pressure distribution at midspan of HIREP stator. b) Predicted bubble volume fraction profiles vs. experiment for bubble column reactor at several liquid superficial velocities.
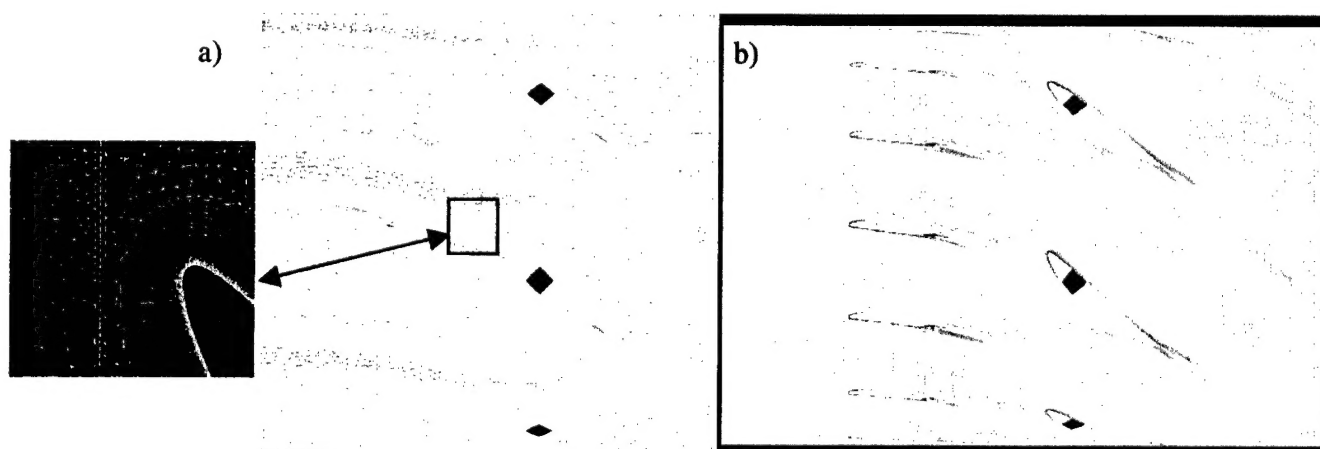

Figure 2. Elements of NPHASE bubbly flow HIREP stage. a) Views of unstructured grid including rotor leading edge detail. Overlaid on grid is snapshot in time of a full unsteady rotor-stator analysis, 6-bubble-field computation, 1/2-cosine inlet bubble number density profile. Shown are contours of volume fraction of 20μm bubble field. b) Snapshot in time of a difference in predicted volume fraction between 20μm and 100 μm bubble fields.

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Wake acoustic propagation modeling. In-water data have been compared with acoustic predictions made using the 2D PE code in horizontal and vertical cuts through the simple, random wake acoustic field. Figure 3 (top panel) shows transmission loss (TL) predicted using PE and a horizontal cut through the simple, structured wake model [4]. Striations in the TL are due to structure in the wake acoustic field. A receiver track is superimposed on the TL field, and (bottom panel) wake loss is calculated by subtracting (20 logR + αR) from the TL at each receiver position. These wake loss predictions provide significantly better agreement with in-water data than the ray tracing predictions.
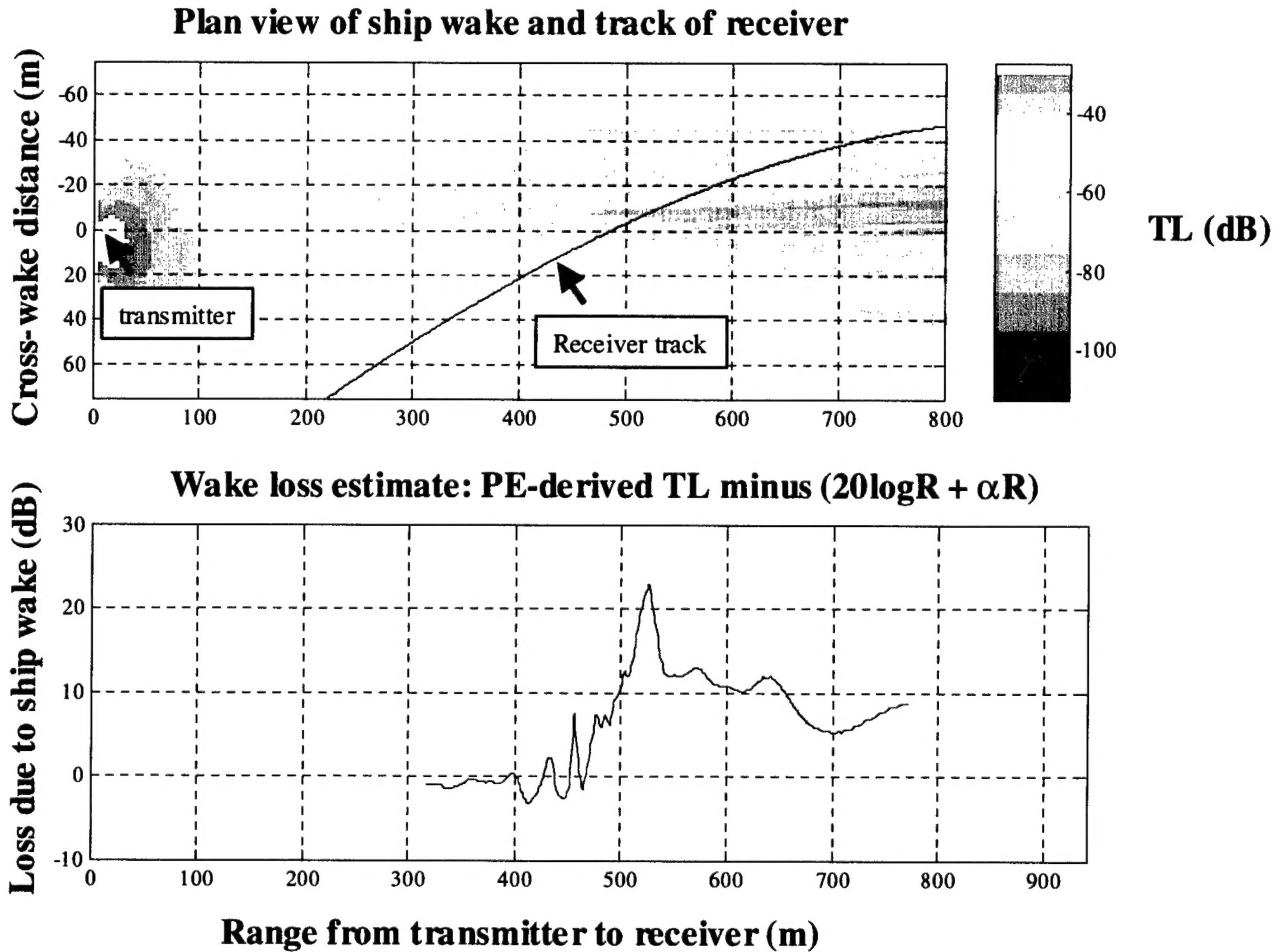

Figure 3: Wake loss predicted using 2D PE and a simple, random wake acoustic field derived from unclassified sources (see text for reference). Top panel: Transmission loss (TL) predicted by 2D PE in a horizontal plane through the ship wake. Striations are due to structure in the wake bubble field. Track of the receiver shown too. Bottom panel: Wake loss along the receiver track estimated by subtracting 20 logR + αr from Tl. Note that wake loss can vary 0-25dB over short distances and is not, in general, range dependent. These results compare well qualitatively with in-water data.

Results to date in development and testing of the 3D PE code are shown in Figure 4, which shows TL predictions for two vertical planes spaced 3° in azimuth. The wake field is plume7 from reference [2]. The vertical axis is depth to 40m and the horizontal axis is range to 800m. Color indicates TL using the same color scale as Figure 3. Source depth is 6m. TL is high (black) at the bottom of each plot due an acoustic "sponge" placed there to absorb energy.
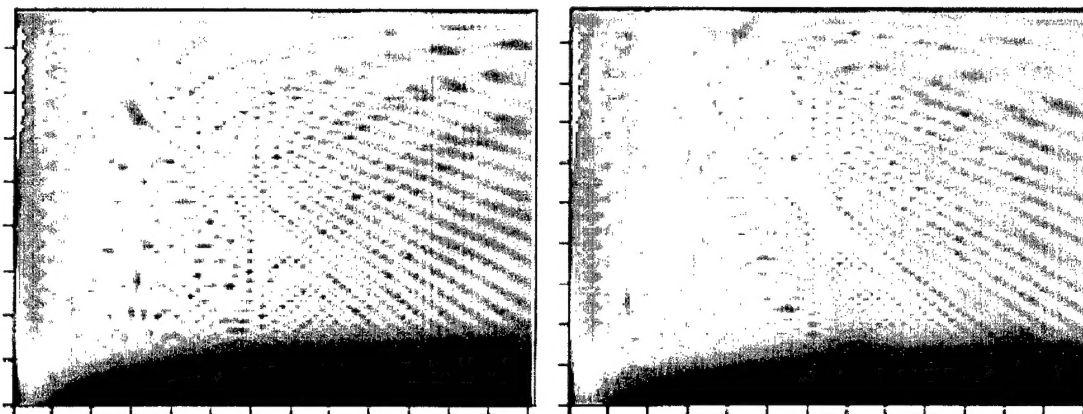
Figure 4: 3D PE predictions of transmission loss through the ship wake. Predictions are for vertical slices 3° apart in azimuth through the same wake field that was used in Figure 3. In each panel, the vertical axes are depth from the surface to 40m, and the horizontal axes are range from 0m to 800m.

IMPACT/APPLICATIONS

Task 1: The motivation for investigating acoustic coherence in the ocean channel is a desire to improve the performance of undersea weapon systems that utilize acoustics to detect, classify and localize the target. Our emphasis is on broadband signals because the undersea weapons development community is increasing bandwidths at traditional weapons frequencies so as to extend down to the multiple kilohertz region. Advanced signal processing architectures are contemplated. Progress depends upon being able to incorporate coherence knowledge or estimates and optimizing the design accordingly.

The entire undersea weapons community is moving toward increased system bandwidth in order to improve signal to interference ratio (SIR) for low Doppler targets, classification performance, and countermeasure resistance. However, the coherence of the propagation channel (and the target echo) across the frequency band, referred to as *frequency coherence,* must be known in order to optimally use increased system bandwidth.
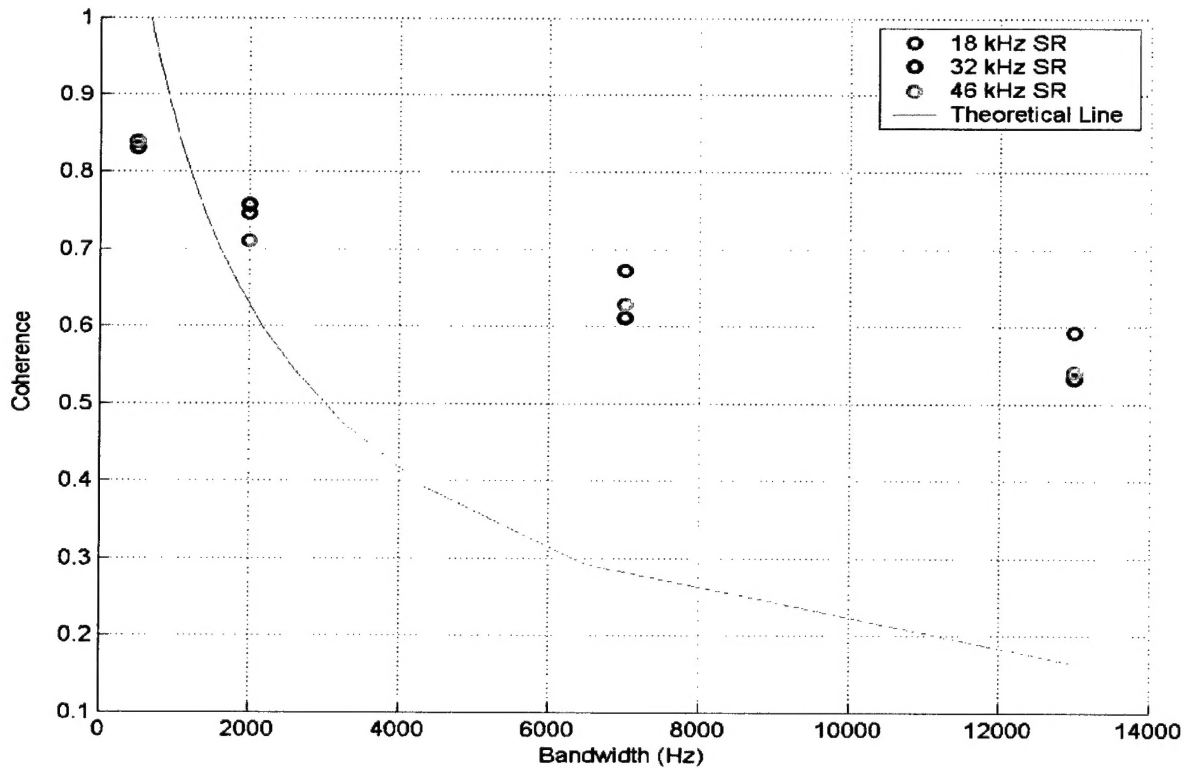
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***Figure 4: Comparison of measured correlation vs signal bandwidth with available theory [1].
Bandwidths up to 13kHz were used in the Oct 01 BBCOH experiment; previous measurements, on
which the theory is based, only utilized bandwidths up to 2kHz. The theory, published in 1974
included shadowing effects, which are not included here. The disparity between theory and
experiment shown above might be reduced with it's inclusion, since most of the current data is for
grazing angles less than 20 degrees.***

Task 2: Understanding and being able to predict acoustic propagation through ship wakes is important
to the US Navy's development of an anti-torpedo torpedo (ATT) that can counter wake homing
torpedoes. Since it is neither feasible nor affordable to conduct at-sea measurements using every ship
class in every environment and using all possible combinations of ATT and threat geometries, a
predictive model is required. Also, acoustic propagation through entrained air in water due to wind-
wave action is important to the development of mine countermeasure systems for use in near-shore
areas.

TRANSITIONS

Task 1: Broadband coherence measurements and models produced under this project may be used in
the design or optimization of wideband signal processors under the Multi-Platform Broadband
Processing Advanced Technology Demonstration (ATD) (Program Officer: Mr. Les Jacobi, ONR
Code 333)., and also the 6.3 Broadband/ Frequency Agility Project. They will likewise be used to
design or optimize channel equalization schemes for acoustic communications applications.

Task 2: The 2D PE propagation model was installed on a classified computer for use under the Torpedo Defense (TD) program at ARL.

RELATED PROJECTS

Task 1: Closely related projects include: Peter Dahl (APL-UW) *High-Frequency Scattering from the Sea Surface and Multiple Scattering from Bubbles*; David Farmer (URI) *Turbulence, bubble distributions and high frequency propagation*, and Bill Hodgkiss and Bill Kuperman (MPL/SIO) *Fluctuations in High Frequency Acoustic Propagation.*
The Multi-Platform Broadband Processing Advanced Technology Demonstration (ATD) (Program Officer: Mr. Les Jacobi, ONR Code 333) has a goal of developing and demonstrating broadband processing across the mid- to high frequency band (weapon, submarine and surface ship platforms). Areas of focus in the ATD are broadband processing using multi-component simultaneous signals and coherent broadband processing. Measurements and modeling of frequency and temporal coherence produced by our work may be of direct relevance to this ATD. The Common Broadband Sonar System (CBASS) is also exploring applications of this technology
Task 2:
- ONR 6.2 Counterweapon development program (Program Officer: T. McMullen)
- ATT Advanced Technology Demonstration (Sponsors at ONR and PMS415, Program Officer: T. McMullen)
- Tripwire Torpedo Defense System (PMS415, Program Officer: T. Goodall)

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Task 2:
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Task 1:
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Yu, W.S., Kunz, R.F., Antal, S.P., Ettorre, S.M. *Unstructured Rotor Stator Analysis of Axial Turbomachinery Using a Pressure-Based Method*, paper to be presented at ASME International Mechanical Engineering Congress and Exposition, New York, NY, November, 2001.

PATENTS

None